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A computer code (SKINTEMP) for predicting transient missile and aircraft heat transfer characteristics

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A COMPUTER CODE (SKINTEMP) FOR PREDICTING TRANSIENT MISSILE AND AIRCRAFT HEAT TRANSFER CHARACTERISTICS

by

Mary L. Cummings

September, 1994

Thesis Advisor: Conrad F. Newberry

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A Computer Code (SKINTEMP) For Predicting Transient Missile And
Aircraft Heat Transfer Characteristics

by

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B.S., United States Naval Academy, 1988

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN ASTRONAUTICAL ENGINEERING

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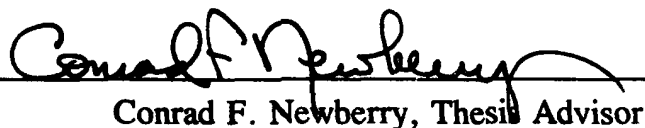
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ABSTRACT

A FORTRAN computer code (SKINTEMP) has been developed to calculate transient missile/aircraft aerodynamic heating parameters utilizing basic flight parameters such as altitude, Mach number, and angle of attack. The insulated skin temperature of a vehicle surface on either the fuselage (axisymmetric body) or wing (two-dimensional body) is computed from a basic heat balance relationship throughout the entire spectrum (subsonic, transonic, supersonic, hypersonic) of flight. This calculation method employs a simple finite difference procedure which considers radiation, forced convection, and non-reactive chemistry. Surface pressure estimates are based on a modified Newtonian flow model. Eckert's reference temperature method is used as the forced convection heat transfer model. SKINTEMP predictions are compared with a limited number of test cases. SKINTEMP was developed as a tool to enhance the conceptual design process of high speed missiles and aircraft. Recommendations are made for possible future development of SKINTEMP to further support the design process.

THESIS DISCLAIMER

The reader is cautioned that the computer program SKINTEMP has not been exercised for all cases of interest. While every effort has been made within the time available to ensure the program is free of computational and logic errors, it cannot be considered validated. Any application of this program without additional verification is at the risk of the user.

TABLE OF CONTENTS

LIST OF SYMBOLS

Symbol	Description	Units
A	Area	ft^2
C_p	specific heat	$BTU/lbm\text{-}°R$
Cp	coefficient of pressure	
g	acceleration	$lbm\text{-}ft/lbf\text{-}sec^2$
h	heat transfer coefficient	$BTU/sec\text{-}ft^2\text{-}°F$
H	enthalpy	BTU/lbm
k	thermal conductivity	$BTU/sec\text{-}ft\text{-}°F$
L	temperature lapse rate	$°R/ft$
m	mass	lbm
N_{NU}	Nusselt number	
N_{PR}	Prandtl number	
N_{RE}	Reynolds number	
q	dynamic pressure	$slug/ft\text{-}sec^2$
q_{stag}	stagnation heating rate	BTU/sec
q_{heat}	heat flow rate	BTU/sec
r	recovery factor	
R	gas constant	$ft\text{-}lbf/slug\text{-}°R$
Rad	nose radius	ft
T	temperature	$°R$
t	time	sec
u	flight velocity	ft/sec
V	velocity	ft/sec
X	distance to point of interest	ft

LIST OF SYMBOLS (CONT)

Symbol	Description	Units
Greek		
ε	emissivity	
γ	specific heat ratio	
σ	Stefan-Boltzmann constant	$BTU/hr\text{-}ft^2\text{-}{}^\circ R^4$
ρ	density	lbm/ft^3
θ	angle normal to freestream	$degrees$
μ	viscosity	$slug/sec\text{-}ft$

Subscripts

aw	adiabatic wall
c	circular
i	time step
L	local condition
o	base value
r	radiation
s	skin
sl	stagnation enthalpy
tL	local stagnation condition
ws	wall enthalpy
∞	freestream condition
t∞	freestream stagnation condition

Superscript

*	reference state

I. INTRODUCTION

A. GENERAL

A FORTRAN computer program has been created to determine transient missile and aircraft mission aerodynamic heating parameters such as heat transfer coefficients, insulated skin temperatures and heat flow rates at some point on the surface a wing or a body of revolution. Required data supplied from the user include material properties and trajectory data such as Mach number, angle of attack, altitude, and time of flight. This program calculates aerodynamic heating parameters for subsonic, transonic, supersonic and hypersonic (no reacting chemistry) flight regimes.

B. BASIC THEORY

The governing equation which serves as the basis for the computer program incorporates both radiative and forced convective heat transfer processes. The thermal energy balance equation for this insulated skin heat transfer case is given by

$$ mC_p \frac{\delta T}{\delta t} = hA(T_{aw} - T_s) - \sigma \epsilon A(T_s^4 - T_r^4) . \qquad (1) $$

The equation written in this form assumes that the adiabatic wall temperature, T_{aw} is greater than the insulated skin temperature, T_s, which is greater than the radiation reference

temperature, T_r. The heat transfer coefficient for convection is obtained from the Nusselt number which is a function of the Reynolds and Prandtl numbers. These dimensionless numbers are defined as

$$(a) \ N_{RE} = \frac{\rho VX}{\mu}, \quad (b) \ N_{PR} = \frac{\mu c_p}{k}, \quad (c) \ N_{NU} = \frac{hX}{k}. \quad (2)$$

Once the complex heat transfer coefficient calculation is performed and the other significant heat transfer parameters determined, a finite difference numerical method can be applied, yielding a skin temperature profile for the specified point of interest.

C. SCOPE

Chapter II details the theory used to develop the SKINTEMP program.

Chapter III describes the actual computer program, its required entry data, expected output data and general program limitations.

Chapter IV presents test case results with the appropriate comparisons, which include intermediate heat transfer calculations. One test case is obtained from a heat transfer textbook and compared to corresponding SKINTEMP results. A less descriptive NASA test case is also compared with SKINTEMP results.

Chapter V provides recommendations for future code development.

II. TRANSIENT HEAT FLOW THEORY

The fundamental concepts used to build the theoretical
model for SKINTEMP involve two basic modes of heat transfer,
convection and radiation. Forced convection is assumed because
the vehicle is propelled through the air by the release of
chemical energy. During supersonic and hypersonic flight,
the local stagnation pressure at the edge of the boundary
layer is assumed to be defined by the stagnation pressure
behind a normal shock wave. Figure 1 illustrates this
concept.
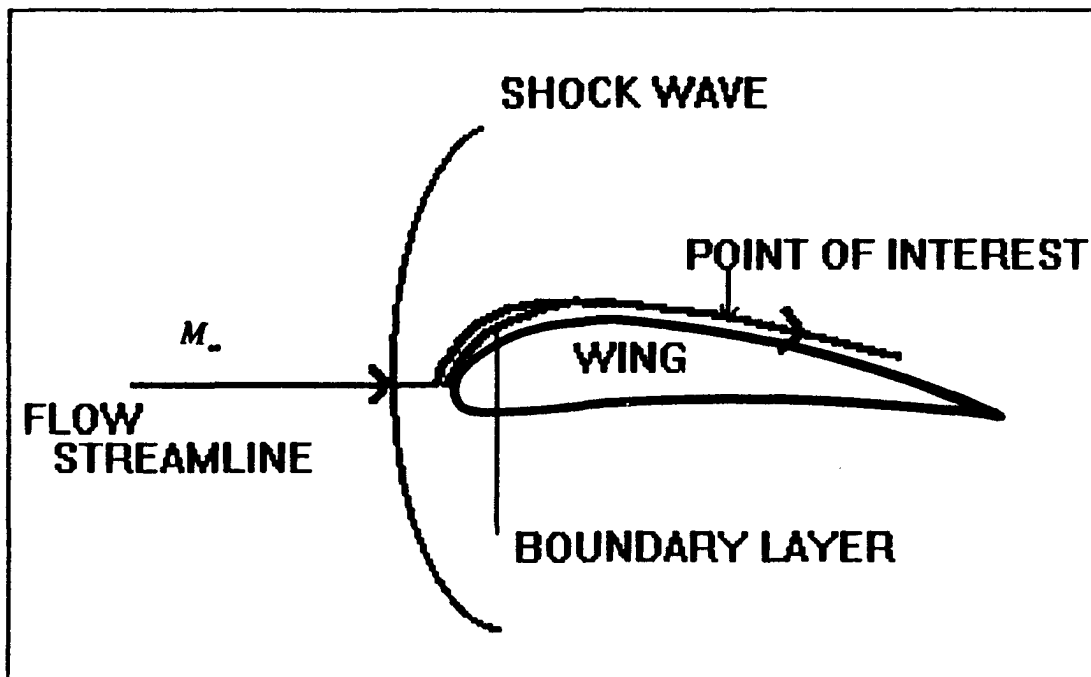
Figure 1. Stagnation pressure at boundary edge

Boundary layer flow is assumed to be turbulent due to the magnitude of the Reynolds number which is generally greater than 500,000. The gas dynamic relations are based on inviscid flow, no reacting chemistry assumptions [Ref. 1].

The primary objective of the computer code is to rapidly compute the transient insulated skin temperatures along the trajectory of the aircraft at a given point somewhere on the surface. To accomplish this, the thermal energy balance equation

$$mC_p\frac{\delta T}{\delta t} = hA(T_{aw} - T_s) - \sigma\epsilon A(T_s^4 - T_r^4) \qquad (1)$$

is solved for T_s using a finite difference method [Ref. 2]. However, before this can be accomplished, the adiabatic wall temperature and the heat transfer coefficient must be determined. The required data for the skin temperature calculations include trajectory parameters (time, Mach number, angle of attack, altitude), material properties (density, material specific heat, emissivity), the location and skin thickness at the point of interest, and a radiation reference temperature. This radiation temperature is the temperature of a distant surface seen by the insulated skin element, which for this program, is either space or the earth.

A. THE ADIABATIC WALL TEMPERATURE

The first parameter needed to determine skin temperature is the adiabatic wall temperature. The adiabatic wall temperature is given by

$$T_{AW} = T_L \left[1 + r \frac{\gamma - 1}{2} M_L^2 \right]. \tag{3}$$

The local Mach number needed for the solution,

$$M_L = \sqrt{\left[\frac{P_{tL}}{P_L}^{(\gamma-1)/\gamma} - 1 \right] \frac{2}{\gamma - 1}}, \tag{4}$$

is dependent on the local pressure and the local stagnation pressure. The speed of the aircraft, whether subsonic or supersonic will determine the local stagnation pressure. If the trajectory profile calls for subsonic flight, then the local stagnation pressure will be

$$P_{tL} = P_L \left[1 + \frac{\gamma - 1}{2} M_\infty^2 \right]^{\gamma/\gamma-1}. \tag{5}$$

If the Mach number is in the supersonic range, the local stagnation pressure is then

$$P_{tL} = P_{t\infty} \left[\frac{\frac{\gamma+1}{2} M_\infty^2}{1 + \frac{\gamma-1}{2} M_\infty^2} \right]^{\gamma/\gamma-1} \left[\frac{2\gamma}{\gamma+1} M_\infty^2 - \frac{\gamma-1}{\gamma+1} \right]^{1/1-\gamma} \tag{6}$$

where

$$P_{t\infty} = P_\infty \left[1 + \frac{\gamma - 1}{2} M_\infty^2 \right]^{\gamma/\gamma-1}. \tag{7}$$

Freestream pressure, temperature, and density are calculated using standard atmosphere property value approximations found in Reference 3.

Local surface pressure is determined using modified Newtonian theory, [Ref. 4] where

$$P_L = C_{pmax}\cos^2\theta q + P_\infty \qquad (8)$$

$$C_{pmax} \equiv \frac{P_{tL} - P_\infty}{q} \qquad (9)$$

$$q = 1/2\rho_\infty V_\infty^2. \qquad (10)$$

Modified Newtonian flow theory has been shown to be applicable for the prediction of local surface static pressures over all surfaces experiencing non-separated flow. [Ref. 5,6] The accuracy of Modified Newtonian flow theory is quite reliable at hypersonic speeds. Its use at subsonic and low supersonic speeds is justified by the continuity and simplicity it provides in the lower Mach number regions where aerodynamic heating rates are so low as to be negligible.

The remaining parameter needed to determine the adiabatic wall temperature is the recovery factor (turbulent flow is assumed), given by

$$r = N_{PR}^{1/3} \qquad (11)$$

where the Prandtl number is

$$N_{PR} \equiv \frac{C_p \mu}{k}. \qquad (12)$$

The specific heat of air used in the Prandtl number is given by [Ref. 2]

$$C_p = .219 + .342E{-}4T_L - .293E{-}8T_L^2. \qquad (13)$$

Thermal conductivity [Ref. 7] and dynamic viscosity [Ref. 2] are also temperature dependent and are given respectively by

$$k = .0141 \left[\frac{707}{T_L + 225} \right] \left[\frac{T_L}{492} \right]^{3/2} \tag{14}$$

$$\mu = \frac{2.27 E\text{-}8 \; T_L^{3/2}}{T_L + 198.7}. \tag{15}$$

B. THE HEAT TRANSFER COEFFICIENT

In order to calculate the heat transfer coefficient, one uses the concept of the reference temperature. The reference temperature is a temperature whose magnitude is typically between that of the wall temperature and freestream temperature and in low speed flow, the reference temperature does become the average of the two [Ref. 2]. This reference temperature more accurately models the temperature distribution that occurs within the boundary layer, which has a significant impact on the skin temperature [Ref. 8]. The transport properties should be evaluated at the reference temperature [Ref. 9] which is defined by

$$T^* = T_L + .5(T_s - T_L) + .22(T_{AW} - T_L). \tag{16}$$

Values for the thermal conductivity, dynamic viscosity, and specific heat used in the Nusselt number are based on this reference temperature.

The Nusselt number can be defined as

$$N_{NU}^* \equiv \frac{h \, X}{k^*}. \tag{17}$$

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Based on experimental data, the Nusselt number can also be written as a function of Reynolds and Prandtl number, [Ref. 2]

$$N_{NU}^* = .0292 \, (N_{RE}^*)^{.8} \, (N_{PR}^*)^{1/3} \tag{18}$$

where the boundary layer is assumed to be turbulent and the Reynolds number is defined as

$$N_{RE}^* \equiv \frac{\rho^* V_L X}{\mu^*} . \tag{19}$$

With these significant variables defined, the thermal energy balance equation can be solved using a simplified finite difference method. This method calculates the temperature value at a future time based on a calculated time increment and the current temperature value.

C. THE SKIN TEMPERATURE

Solution of the thermal energy balance equation for the incremental skin temperature yields

$$T_{s,i+1} = [hA(T_{aw} - T_s) - \sigma\epsilon A(T_s^4 - T_r^4)] \frac{\delta t}{mC_p} + T_{s,i} . \tag{20}$$

For stability purposes, the time interval associated with this finite difference method is given by

$$\Delta t \leq \frac{mC_p}{h+h_r} \tag{21}$$

where

$$h_r = A\epsilon\sigma \, [T_s^3 + T_s^2 T_r + T_r^2 T_s + T_r^3] . \tag{22}$$

Each progressive skin temperature is dependent on the previous temperature, heat transfer coefficient and adiabatic

wall temperature. The time interval choice is critical and must meet the stability requirement of the finite difference method. This stability requirement, which prevents the solution from diverging, is given by

$$\frac{\Delta t (h + H_r)}{m C_p} \leq 1. \tag{23}$$

To meet this requirement, the time interval was chosen as

$$\Delta t = .25 \frac{m C_p}{h + H_r}. \tag{24}$$

D. THE HEAT FLOW RATE

The heat flow rate is dependent on the location of the stagnation heating point. In the stagnation region for the axisymmetrical and two dimensional platforms, the maximum stagnation point is 70 degrees from the centerline [Ref. 10] and the stagnation heating rate is given by [Ref. 11]

$$q_{stag} = \frac{17600}{\sqrt{Rad}} \sqrt{\frac{\rho}{\rho_o}} \left[\frac{u}{u_c}\right]^{3.15} \left[\frac{H_{sl} - H_{ws}}{H_{sl} - H_{w545}}\right]. \tag{25}$$

Away from the stagnation point but prior to regions that can be treated as flat plates, the heat flow rate [Ref. 10] is assumed to be

$$q_{heat} = q_{stag} \cos(\theta)^{3/2}. \tag{26}$$

Otherwise, in areas where flat plate assumptions hold, the heat flow rate is

$$q_{heat} = hA(T_{aw} - T_s) - \sigma\epsilon A(T_s^4 - T_r^4). \tag{27}$$

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III. THE SKINTEMP COMPUTER PROGRAM

A. THE COMPUTER CODE STRUCTURE

The flow logic used for the SKINTEMP program is illustrated in Figure 2. The program is divided into four major sections, data entry, atmospheric property generation, skin temperature calculations and data output.

The first module contains the data entry loop. The data can be entered via two methods, keyboard entry or file entry. If the user chooses to utilize keyboard entry, the program will prompt the user for the specific data. Each entry should be followed by a keyboard hard return. The file entry method requires the user to create an external file using any standard editor containing all the required information. For file entry, the correct syntax to enter at the prompt is SKINTEMP.in. The .in refers to the entry file; any input file used must have the .in included in the file name. This command allows data to be read automatically by the input subroutine.

The important note to remember is that for file entry, each piece of fixed point data must be placed on a separate line and the entry data must correlate with the data requested by the program. If the program terminates with an error message, this would be the first place to check for mistakes.

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The second section of the code generates standard atmospheric values that are needed for the freestream pressure, temperature, and density calculations. The governing equations used to model atmospheric properties are divided into two regions, gradient and isothermal [Ref. 3]. The gradient relationships are

$$\frac{\rho}{\rho_o} = \frac{T}{T_o}^{-[g/LR +1]} \tag{28}$$

$$\frac{P}{P_o} = \frac{T}{T_o}^{-[g/LR]} \tag{29}$$

$$T = L(h-h_o) + T_o. \tag{30}$$

There are several isothermal regions in the atmosphere. While the temperatures remain constant in each of these isothermal regions, the temperatures of the gradient regions will vary. [Ref. 3] The pressure and density relationships for isothermal regions are given by

$$\frac{P}{P_o} = e^{-g[h-h_o]/RT} \tag{31}$$

$$\frac{\rho}{\rho_o} = e^{-g[h-h_o]/RT}. \tag{32}$$

With these relationships, the atmosphere is modeled to 260,000 feet with isothermal layers from approximately 36,000 to 82,000 feet (temperature = 392.4 °R, density = .00071 slug/ft^3, pressure = 476 lb/ft^2) and 154,000 to 174,000 feet (temperature = 509 °R, density = .00000303 slug/ft^3, pressure = 2.6419 lb/ft^2).

The third major section of SKINTEMP is the calculation of the skin temperature. This section is a large counted loop because each successive skin temperature is dependent on the previous temperature calculated. This loop is partitioned into four sections. The first section calculates adiabatic wall temperature and the second determines the heat transfer coefficient. These two calculations lead to the skin temperature solution, which is in the third section. The fourth and final section calculates the heat flow rate. [Ref. Chapter II] Appendix A contains the actual computer program. The initial documentation of the program contains a list of the variables, their definitions, and the English units used.

It is important that the user understand the differences between the time values used throughout SKINTEMP. The user should input time intervals that best linearize the trajectory. In other words, whenever the Mach number, altitude or angle of attack is changing, this time and associated flight parameters should be a data entry point. These time intervals can be the print out time intervals but SKINTEMP also allows the user to print the results at different time intervals if desired. These input and output time intervals are independent of the time interval chosen for the heat balance calculations. Figure 3 demonstrates these differences and should be used as a reference when developing a data entry strategy for SKINTEMP.

BLOCK A

READ INPUT DATA FROM USER OR FILE INTO ARRAY

↓

GENERATE ATMOSPHERIC TABLES

BLOCK B ↓

TAW IS COMPUTED USING

P_{tL}, V_∞, q, θ_L, C_{pmax}, P_L, M_L, T_{tL}, k, C_p, μ, N_{PR}, I, T_L

↓

h IS COMPUTED USING

T^I, ρ^I, μ^I, V_L, N_{RE}^I, C_p^I, k^I, N_{PR}^I, N_{NU}^I

↓

SKIN TEMPERATURE IS COMPUTED AFTER CALCULATING δt

↓

HEAT FLOW RATE COMPUTED BASED ON STAGNATION POINT

↓

IF $\sum \delta t <$ *INPUT TIME INTERVAL*

GOTO BLOCK B

↓

IF $\sum \delta t \geq$ *INPUT TIME INTERVAL*

PRINT OUTPUT
GOTO BLOCK A

Figure 2. SKINTEMP Flowchart

See Chapter II for a complete description of the relationships needed to obtain the desired results.

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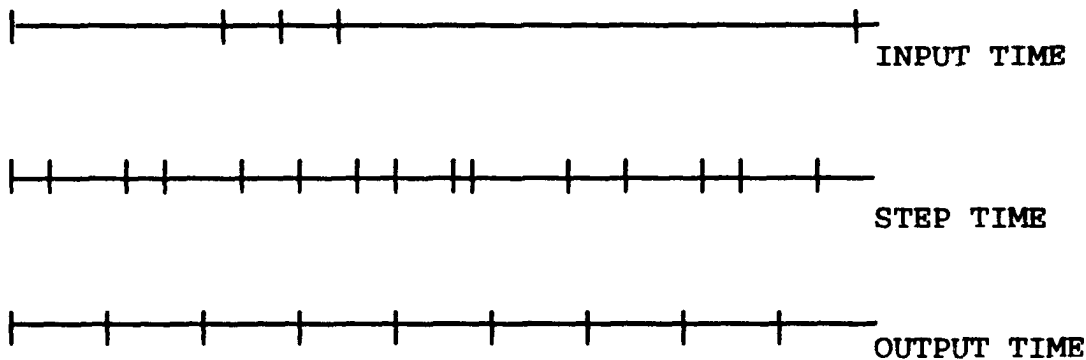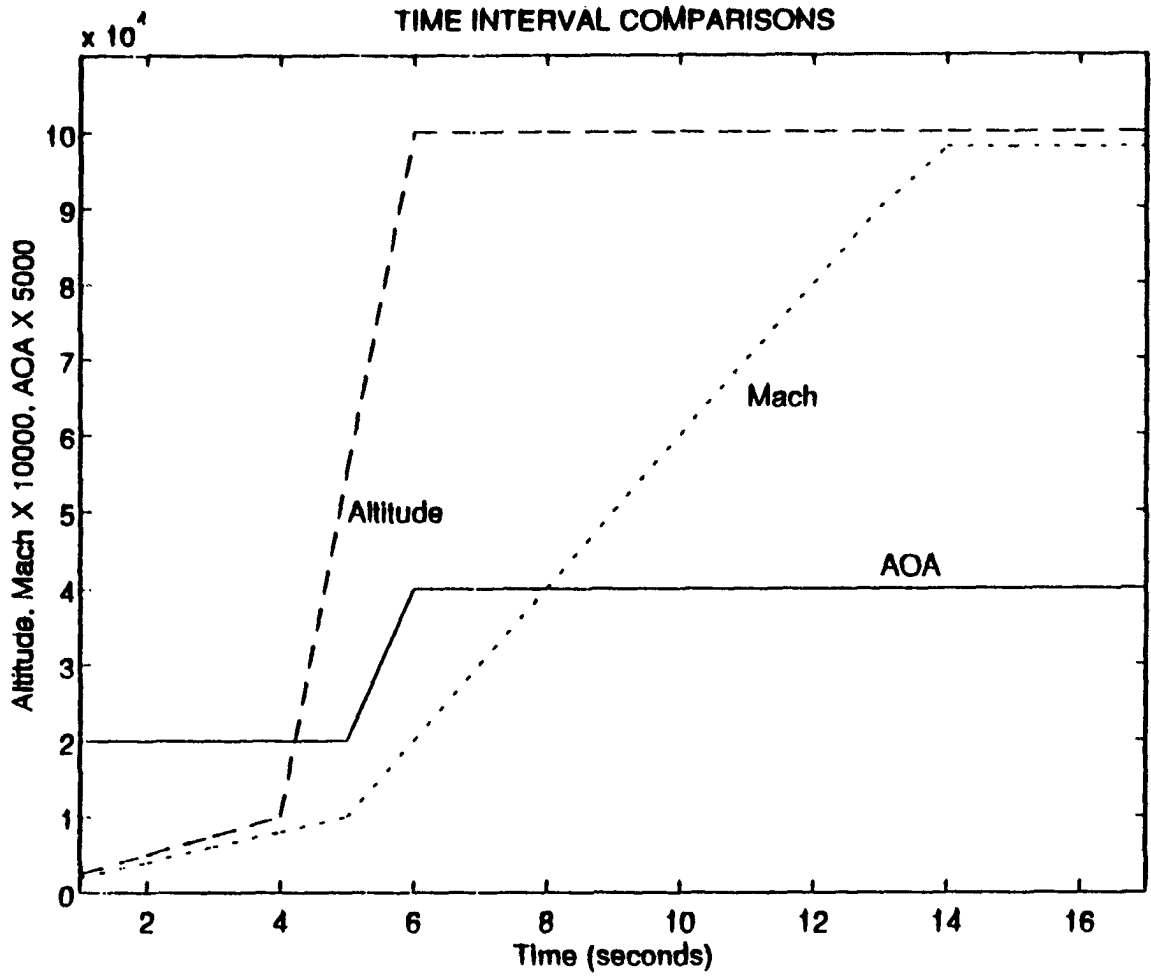
Figure 3. Time Interval Comparison

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B. REQUIRED DATA INPUT

SKINTEMP allows the user to enter data through the keyboard or through an external file. In either case, the following data is required to successfully run the program:

- The shape of the body, which must be either two dimensional or axisymmetric

- If a two dimensional wing shape is selected, the wing sweep (degrees)

- The launch surface skin temperature of the vehicle (°F)

- For each time interval, the Mach number, the angle of attack (degrees), and the altitude (feet)

```
*****************************************
     WARNING: Entering a Mach number of
              zero will cause the
              program to abort. See
              Section D. below.
*****************************************
```

- The distance from the nose or leading edge to the point of interest (feet)

- The thickness of the surface at the point of interest (inches)

- The nose radius (feet)

- The material density (pound per cubic foot)

- The material emissivity (dimensionless)

- The material specific heat (BTU per pound-°F)

- The orientation of the surface. Does the surface face the earth or space for the majority of the flight? This provides the radiation reference temperature of -460 °F for space and 60 °F for the earth. (°F)

- The angle from the unit surface normal of the skin element to the freestream (degrees)

- The output time interval (seconds)

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C. SKINTEMP OUTPUT

The output of the computer program is in tabular form. The user can choose any time interval for printing independent of the data time entries. See Appendix B for an sample output. SKINTEMP will also produce an external UNIX file named Fort.3 which produces a table of values for the time and skin temperature that can be used in typical engineering graphics/plotting programs.

The program is clearly documented and the print subroutine is the last section in the program. The output format is as follows:

TIME	ADIABATIC WALL TEMPERATURE	HEAT TRANSFER COEFFICIENT	SKIN TEMPERATURE	HEAT FLOW RATE
(sec)	(°Rankine)	(BTU/sec-ft^2-°F)	(°Rankine)	(BTU/sec)

D. SKINTEMP LIMITATIONS

The purpose of this code is to provide a design tool for conceptual missile and aircraft design projects. At the present time, SKINTEMP can only calculate the transient heat parameters for bodies that are either two dimensional or axisymmetric body shaped. See Chapter V for future recommendations for code expansion.

Another limitation and perhaps the most important for user information is that at no time can the Mach number entered be

equal to zero. The reason for this is that in the calculation for $C_{p,max}$, dynamic pressure is the divisor. $C_{p,max}$ and dynamic pressure are given by

$$C_{p,max} = (P_{tL} - P_{\infty})/q \quad (9) \quad where \quad q = 1/2\rho V^2 = \frac{\gamma}{2} P M^2. \quad (33)$$

A Mach number of zero will cause $C_{p,max}$ to be undefined. If this occurs, the program will terminate without results. If a Mach number of zero is the actual value achieved in the trajectory, a small value should be entered, i.e., .001 Mach.

The last limitation is the array size of the input data. At the present time, the array size of data points entered is 100. If more than 100 data points are desired by the user, the array size should be altered in the body of SKINTEMP. The array dimension statement is the first to occur after the initial documentation and the maximum limit is dictated by the version of FORTRAN being used.

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IV.   TEST CASE RESULTS

A.   TRUITT TEST CASE

The test case used to validate SKINTEMP is based on an example skin temperature problem from Robert W. Truitt's text *Fundamentals of Aerodynamic Heating*, [Ref 12].   The example missile profiled is axisymmetric in shape and 40 feet in length.   The skin material used is Inconel steel and the skin thickness of the material at the point of interest, 20 feet from the nose, is .00504 inches.   The flight trajectory data are given in Figure 4.
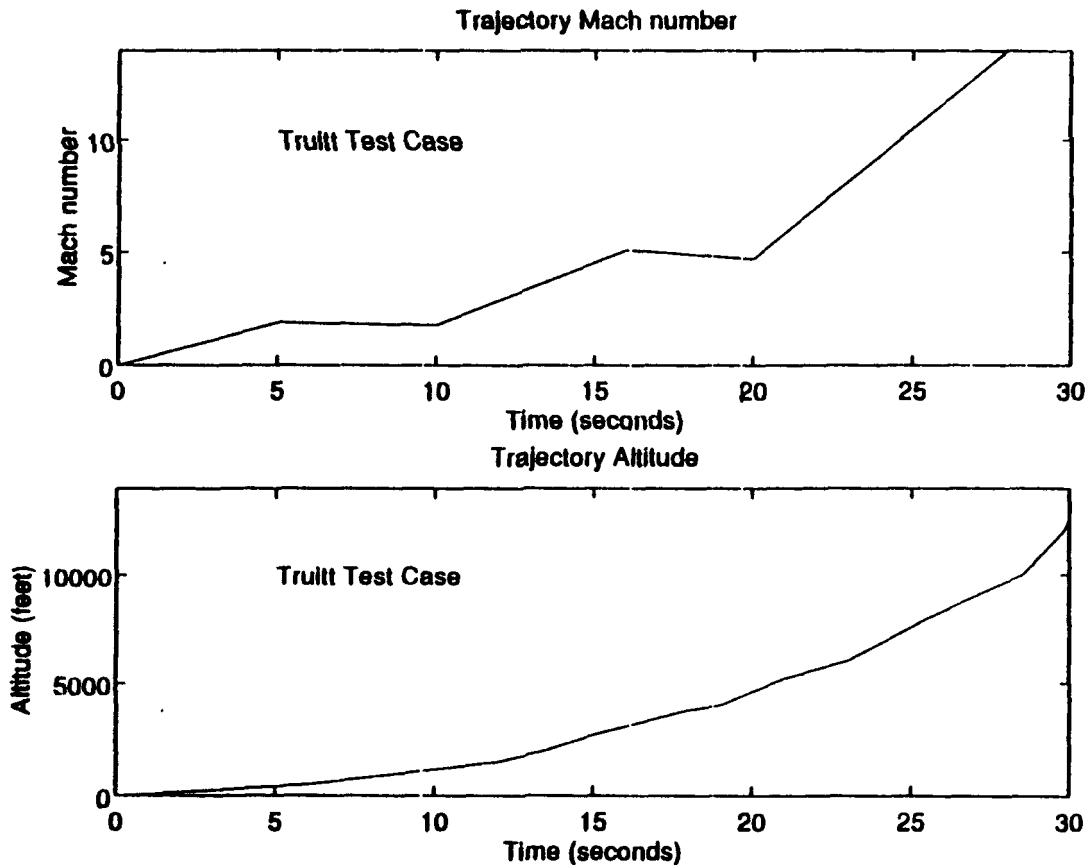
Figure 4. Truitt's trajectory data

Truitt assumes turbulent flow but does not use specific local or reference state conditions. Instead, he assumes freestream conditions throughout the calculations. This approach is responsible for at least some of the noticeable deviation in the comparative results [Ref. Section 2].

A Runge - Kutta numerical integration method for the skin temperature calculation is employed by Truitt rather than the finite difference method used in SKINTEMP. This difference in approach was one of the primary reasons this test case was used. Similar results from two different equivalent numerical methods tend to confirm results.

1. Data Comparisons

Throughout Truitt's skin temperature calculation example several intermediate heat transfer and fluid flow parameter values are defined. These computed values include freestream static pressure and temperature, Reynolds number and the computed skin temperature (based on freestream properties). The comparisons of these parameters are listed in the following graphs and tables to validate SKINTEMP and illustrate some of the theoretical differences between calculation methods.

a.   Freestream Pressure Comparison

Figure 5 graphically displays the difference in freestream static pressures while Table 1 details the exact values computed. Truitt's values for freestream static atmospheric density are not as close to the NACA standard atmosphere [Ref. 13] as the SKINTEMP code calculations and the slight divergence in values contributes to the difference in the predicted skin temperatures.
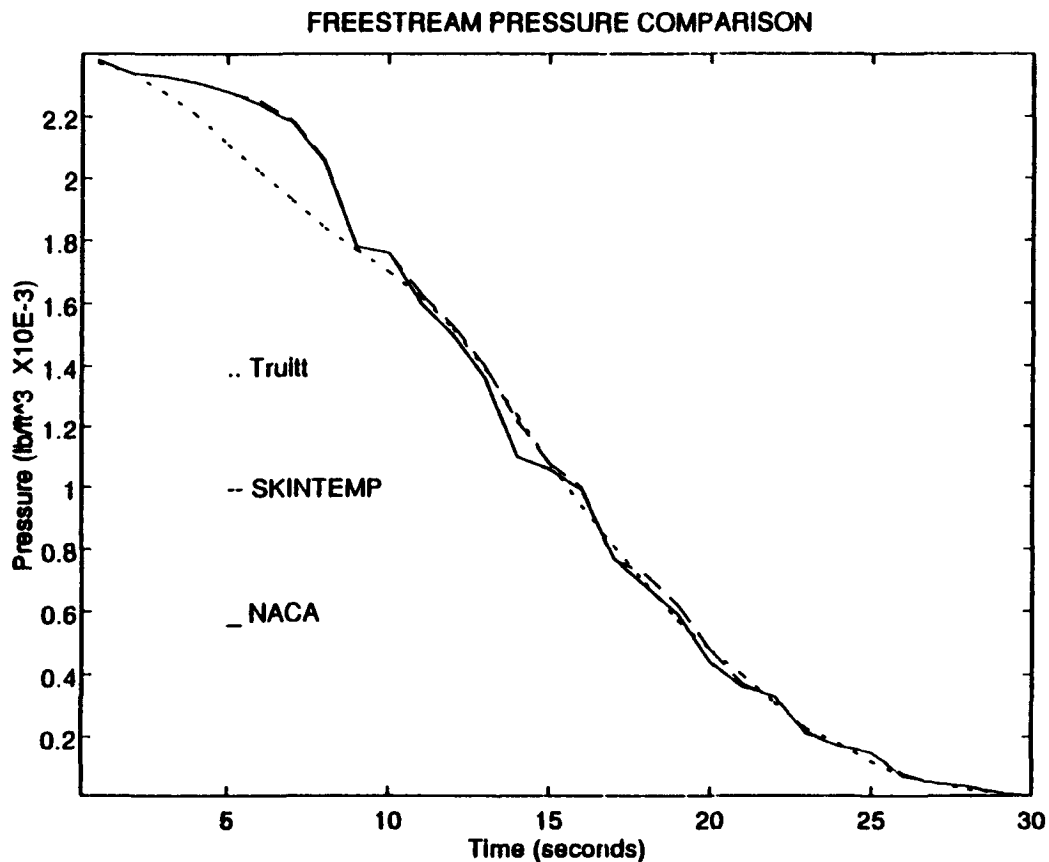
Figure 5.   Freestream static pressure comparison

TABLE 1. FREESTREAM PRESSURE COMPARISON FOR TRUITT'S TRAJECTORY

TIME (SECONDS)	TRUITT (LB/FT^3)	SKINTEMP (LB/FT^3)	NACA (LB/FT^3)
1	.00237	.00238	.00238
2	.00234	.00234	.00234
3	.00228	.00233	.00233
4	.00221	.00231	.00231
5	.00211	.00228	.00228
6	.00202	.00225	.00224
7	.00193	.00219	.00218
8	.00184	.00206	.00205
9	.00177	.00178	.00178
10	.00170	.00176	.00176
11	.00162	.00163	.00160
12	.00152	.00153	.00150
13	.00139	.00140	.00136
14	.00124	.00122	.00121
15	.00108	.00108	.00106
16	.00094	.00100	.00099
17	.00081	.00077	.00077
18	.00069	.00072	.00068
19	.00057	.00062	.00059
20	.00048	.00048	.00044
21	.00040	.00037	.00036
22	.00031	.00033	.00033
23	.00023	.00022	.00021
24	.00018	.00017	.00017
25	.00012	.00015	.00015
26	.00007	.00008	.00007
27	.00005	.00005	.00005
28	.00003	.00004	.00004
29	.00002	.00001	.00002
30	.00001	.00001	.00001

a. *Temperature Comparison For Truitt's Trajectory*

Figure 6 and Table 2 compare Truitt's freestream temperature to SKINTEMP's freestream and reference static temperature. The freestream static temperature calculations compare favorably. Again, the divergence in values can be partially attributed to differences in atmospheric modelling.

Local temperatures are compared with the freestream temperatures to illustrate the difference of using local atmospheric properties instead of freestream properties. SKINTEMP uses local conditions for the heat transfer calculations while Truitt utilizes the freestream conditions. Temperatures near the skin of a hypersonic vehicle will be much higher than the surrounding freestream air due to boundary layer interactions (i.e. skin friction). Thus, calculations using freestream properties are expected to be more approximate than those using the local conditions.
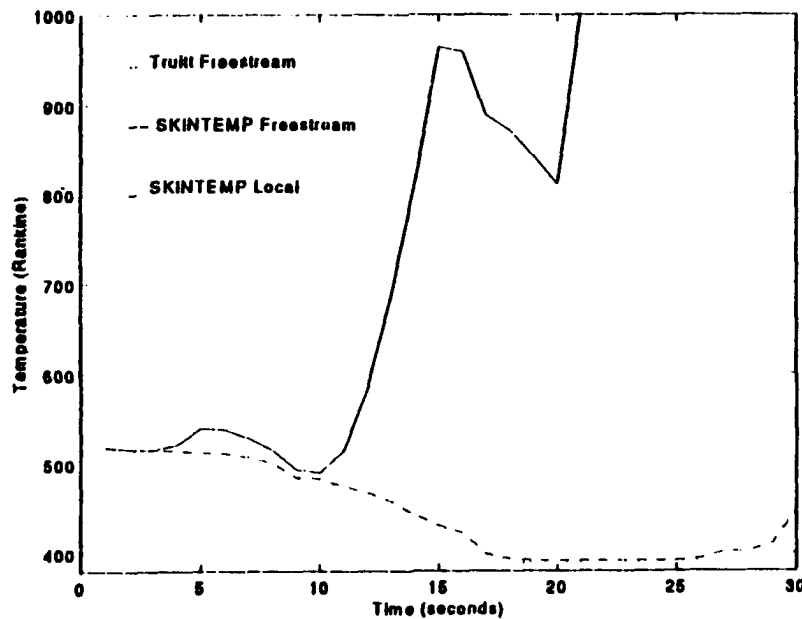
Figure 6. Temperature Comparison

22

TABLE 2.   TEMPERATURE COMPARISON FOR TRUITT'S TRAJECTORY.

TIME (SECONDS)	TRUITT FREESTREAM (^{0}RANKINE)	SKINTEMP FREESTREAM (^{0}RANKINE)	SKINTEMP LOCAL (^{0}RANKINE)
1	519	519	519
2	516	517	517
3	514	516	516
4	510	515	522
5	505	513	540
6	499	512	539
7	494	508	529
8	489	501	516
9	484	485	494
10	480	483	490
11	474	475	515
12	467	468	584
13	457	458	686
14	442	443	812
15	432	431	964
16	417	423	959
17	402	399	889
18	390	394	872
19	390	392	842
20	390	392	811
21	390	392	1007
22	390	392	1273
23	390	392	1518
24	391	392	3036
25	391	392	3527
26	391	394	4074
27	391	402	4742
28	391	402	4761
29	412	411	5492
30	452	447	6291

b. Reynolds Number Comparison For Truitt's Trajectory

The difference in theoretical approaches is very apparent when comparing the Reynolds numbers in Figure 7 and Table 3. Truitt's Reynolds number calculations are very close to SKINTEMP's initial calculations, but again, the divergence in freestream atmospheric properties clearly has an impact on the freestream Reynolds number. The only significant consideration is that this difference becomes larger as the program builds on data from the previous time step.

Figure 7 clearly illustrates that the reference state Reynolds number is significantly smaller than the freestream value. Recall that the reference state utilizes the local flow field values at the edge of the boundary layer with the transport properties evaluated at the reference temperature, and that the Reynolds number is given as

$$N_{RE}^{*} = \frac{\rho^{*} V X}{\mu^{*}},$$ (18)

where

$$\rho = P/RT$$ (34)

$$V = M\sqrt{\gamma R T}$$ (35)

and

$$\mu = \frac{2.27E\text{-}8 \ T_L^{3/2}}{T_L + 198.7}.$$ (15)

The Reynolds number is inversely proportional to the temperature. Use of the local values for temperature, which are significantly larger than the freestream values of temperature, will cause the Reynolds number to decrease.

Another parameter that will contribute to a difference in Reynolds number calculations is the relationship used to determine viscosity, equation 15. Truitt did not utilize the same relationship and even though the values are of the same magnitude, the difference only adds to the deviation in results.
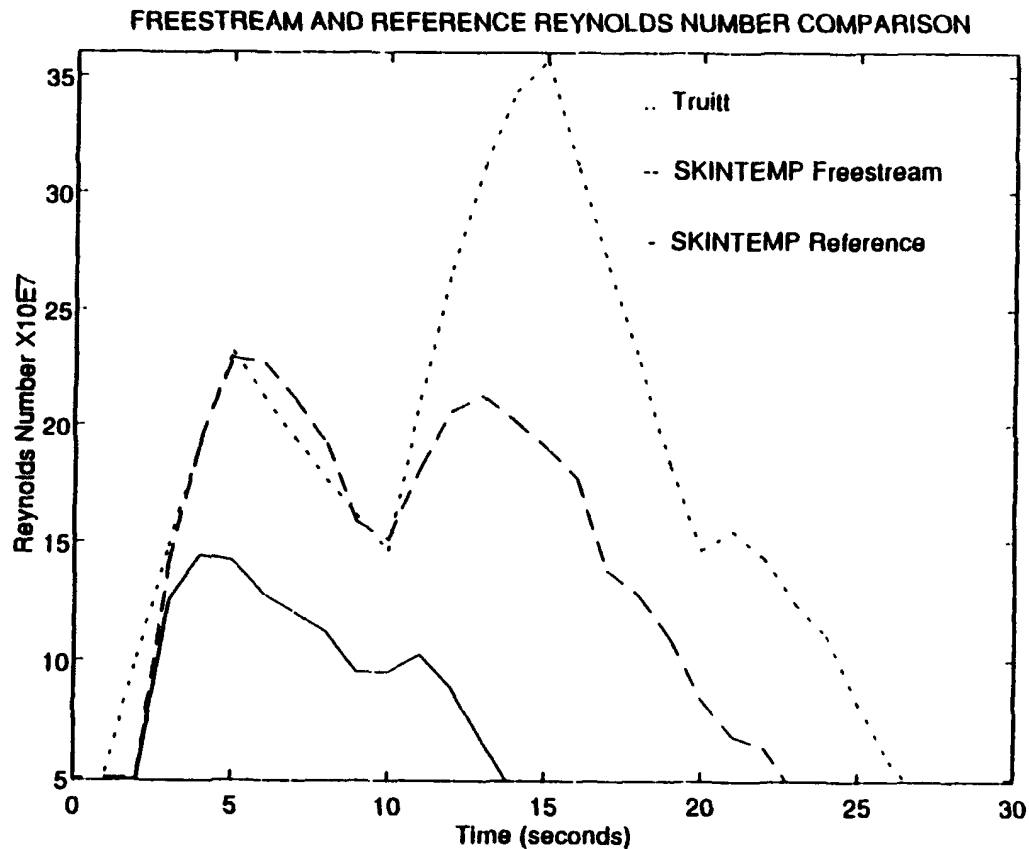
Figure 7.   Reynolds Number Comparison

TABLE 3. REYNOLDS NUMBER COMPARISON FOR TRUITT'S TRAJECTORY

TIME (SECONDS)	TRUITT RE ($\times 10^7$)	SKINTEMP RE FREESTREAM ($\times 10^7$)	SKINTEMP RE REFERENCE ($\times 10^7$)
1	5.290	5.039	4.993
2	10.092	5.051	4.972
3	14.790	14.081	12.528
4	19.270	19.329	14.424
5	23.186	22.908	14.204
6	21.274	22.693	12.772
7	19.408	21.189	11.994
8	17.622	19.188	11.192
9	16.136	15.839	9.513
10	14.614	15.066	9.514
11	21.130	18.134	10.223
12	26.744	20.591	8.881
13	31.116	21.301	6.626
14	34.338	20.262	4.515
15	35.660	19.013	3.144
16	31.030	17.679	2.515
17	26.822	13.764	1.865
18	22.762	12.733	1.777
19	18.212	10.984	1.584
20	14.644	8.447	1.279
21	15.436	6.840	1.004
22	14.336	6.380	.770
23	12.356	4.406	.437
24	11.040	3.513	.298
25	8.280	3.124	.230
26	5.764	1.724	.117
27	4.212	1.173	.072
28	2.754	1.171	.071
29	1.902	.906	.049
30	.942	.320	.017

c. *Skin Temperature Comparison*

Figure 8 and Table 4 compare the final skin temperature calculations between Truitt and SKINTEMP.

TRUITT SKIN TEMPERATURE PREDICTION COMPARISON
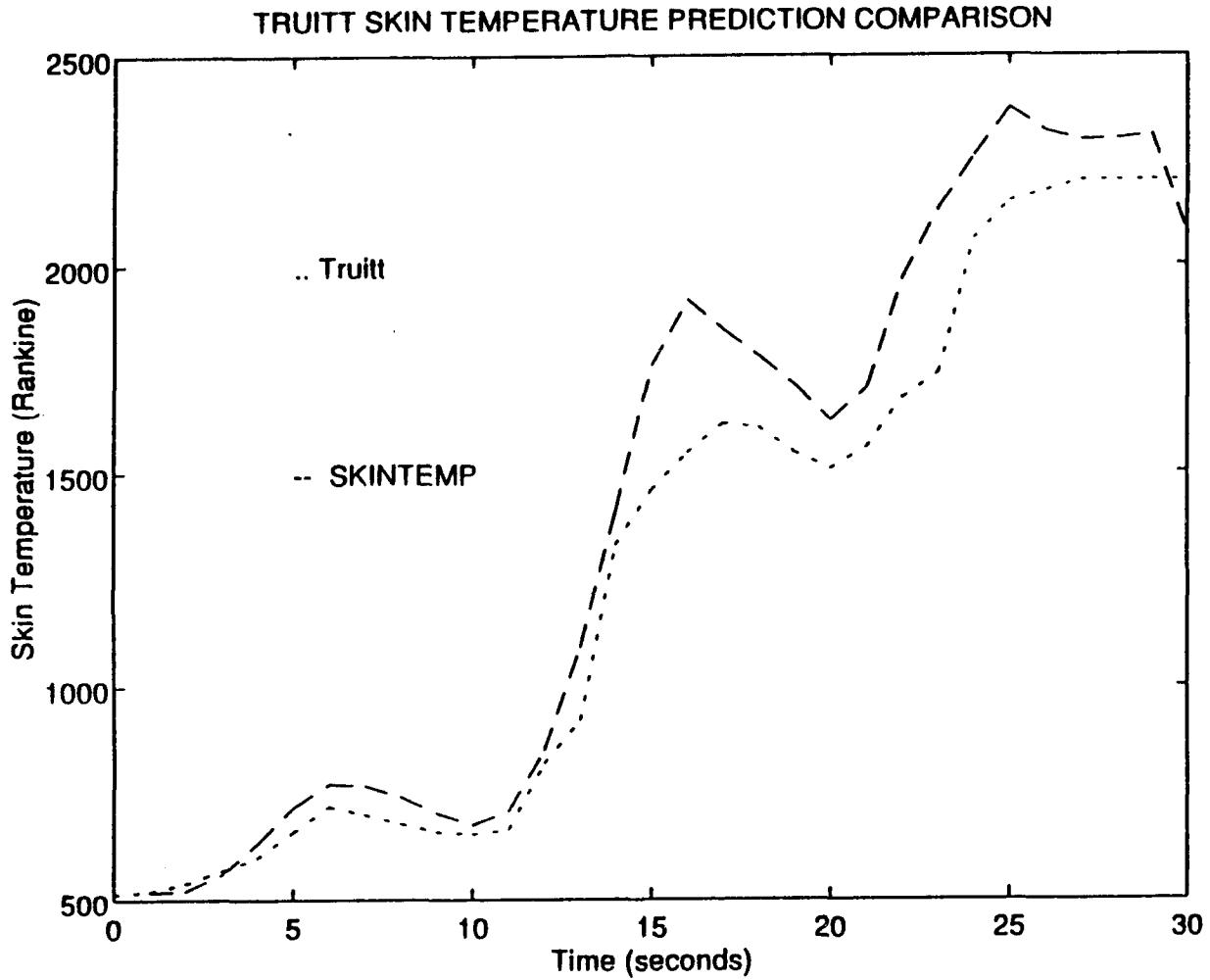
Figure 8. Skin Temperature Comparison

TABLE 4. SKIN TEMPERATURE COMPARISON FOR TRUITT'S TRAJECTORY

TIME (SECONDS)	TRUITT (^{0}RANKINE)	SKINTEMP (^{0}RANKINE)
1	520	519
2	540	522
3	570	560
4	600	633
5	660	717
6	720	772
7	700	767
8	680	742
9	660	704
10	655	677
11	665	707
12	820	850
13	920	1091
14	1330	1408
15	1460	1761
16	1550	1917
17	1620	1845
18	1610	1781
19	1550	1711
20	1510	1626
21	1560	1704
22	1680	1968
23	1740	2132
24	2060	2259
25	2150	2375
26	2175	2319
27	2250	2297
28	2250	2300
29	2250	2310
30	2250	2071

1. Results From Truitt's Trajectory

The graphs and tables indicate comparable results in the two different methods of calculating skin temperature. There are numerous reasons for the slight differences in the results. The discrepancy in standard atmosphere values leads to significant differences in the aerodynamic parameters, which cause marked deviations in the heat transfer coefficients, and the adiabatic wall and skin temperatures.

Another major difference is the use of the reference state in SKINTEMP and the freestream state in Truitt's test case. Using the reference condition instead of the freestream state is considered to be the more correct model of what is actually occurring aerodynamically. One aspect of this difference is manifested in the Reynolds number calculation. Despite the significant difference in Reynolds numbers used to compute the Nusselt number, the results are nearly the same. Recall that to compute the Nusselt number, the Reynolds number is raised to the 0.8 power. Large differences in Reynolds number between the two methods are minimized in this calculation, allowing the skin temperatures to more closely correspond with one another.

Truitt also uses varying skin material specific heats while SKINTEMP assumes an average constant specific heat. This does not cause a noticeable change in skin temperature calculations but does account for a few degrees of difference. The choice of time constants is also critical for stability

purposes. Truitt uses a time step of two seconds while the average time constant step generated by SKINTEMP is 0.3 seconds. As indicated by Truitt, the smaller the time constant, the more accurate the results. Truitt used the larger time constant for ease in calculations because they were all hand computed. With all other variables being equal, the calculation of skin temperatures with the more simplified finite difference method versus the Runge-Kutta method is expected to give the same degree of accuracy, provided the time step is small.

While the Runge-Kutta integration method is an accurate numerical method, Truitt did not have the same computer capabilities that are in use today and the current standard atmosphere tables are considered to be more accurate than those Truitt used. Even though the SKINTEMP results are on average nine percent greater than Truittt's results, the skin temperature curves are similar with SKINTEMP producing the more conservative worst case results.

A. NASA TEST CASE

NASA AMES provided an additional test case for SKINTEMP verification. The trajectory is typical of a Single-Stage - To-Orbit (SSTO) rocket powered vehicle and the point of interest is 75 feet aft of the nose. The thickness of this point of interest is 0.035 inches and the material at this point is Tailorable Advanced Blanket Insulation (TABI).

There is a body angle of incidence of 13 degrees in addition
to the varying angle of attack experienced through flight.
Figure 9 graphically depicts the results and is followed by
the detailed listing of skin temperatures.

NASA SKIN TEMPERATURE PREDICTION COMPARISON
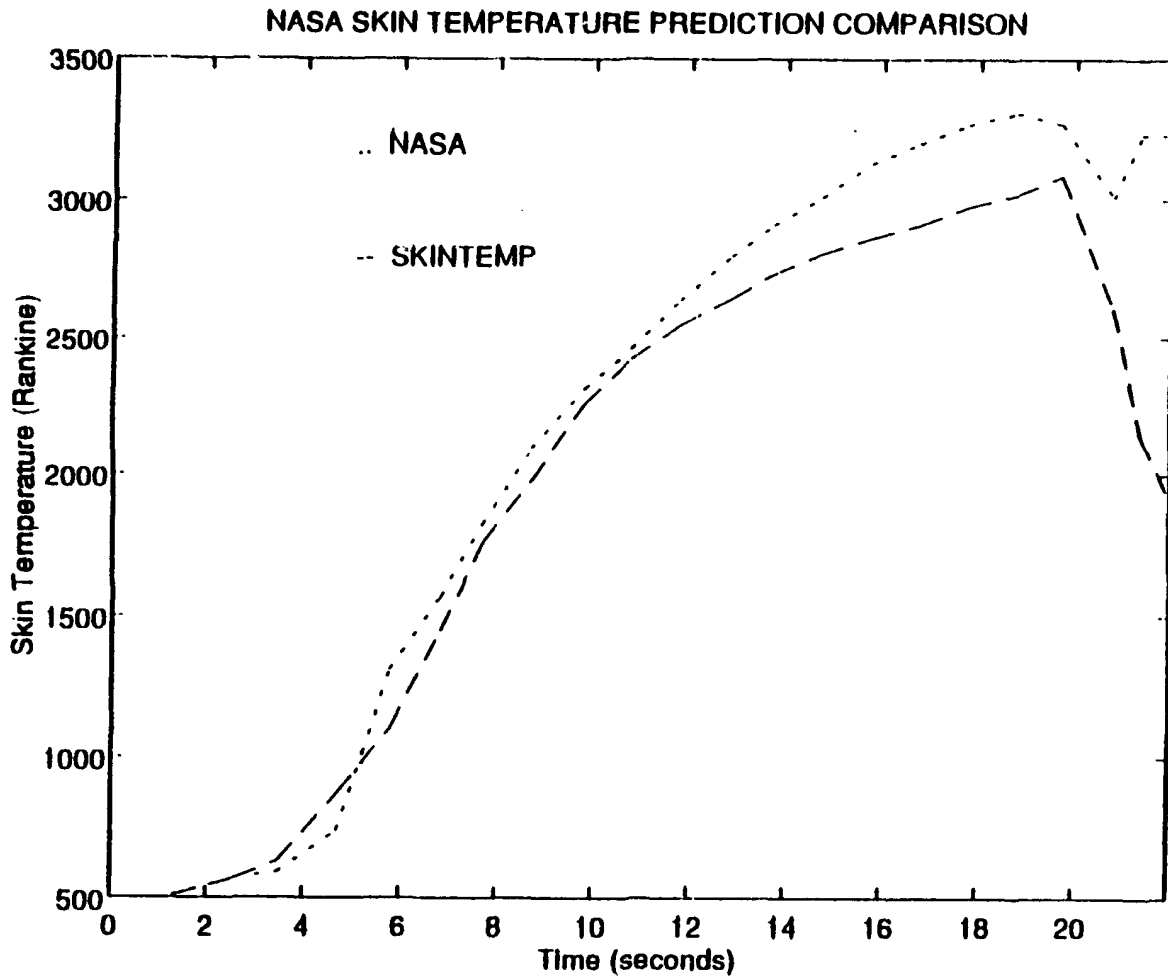
Figure 9. NASA Skin Temperature Comparison

TABLE 5. SKIN TEMPERATURE COMPARISON FOR NASA AMES TEST CASE

TIME (SECONDS)	NASA (°RANKINE)	SKINTEMP (°RANKINE)
1.3	511	511
2.61	571	570
3.48	590	630
4.69	738	870
5.78	1313	1104
6.82	1570	1449
7.70	1821	1756
8.71	2094	1979
9.81	2318	2262
10.76	2463	2424
11.79	2637	2550
12.85	2799	2645
13.72	2912	2733
14.72	3011	2806
15.75	3127	2864
16.75	3200	2911
17.75	3265	2974
18.75	3308	3019
19.70	3267	3084
20.78	3008	2606
21.38	3231	2133

1. Results From NASA Trajectory

Again, the results from the two skin temperature calculation methods compare favorably. The NASA test case was also based on freestream conditions with surface pressures given by tangent wedge/cone theory. While the use of freestream conditions is not theoretically correct, there has been significant experimental data generated to justify this assumption [Ref. 14]. However, these assumptions are best used for upper surfaces. SKINTEMP is not limited to this assumption and can correctly calculate skin temperatures for upper and lower surfaces.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The SKINTEMP computer program was developed as a tool for use in the conceptual design of high speed missiles and aircraft. It can be used over a wide range of trajectories, profiles and configurations and rapidly yields results that enable the user to easily investigate changes in material characteristics and flight parameters without having to employ more complex and cumbersome calculations. As with any computer program, the results can only be as good as the data entered. This is especially true of SKINTEMP because valid results can only be expected if the trajectory is accurately modeled.

Validation of SKINTEMP was achieved using a textbook skin temperature calculation example and a more current NASA test case. SKINTEMP compared with the NASA and Truitt test cases suggest that the SKINTEMP results are reasonable. While each of the methods has its own merits, the fundamental theoretical base, direct approach and simplicity of SKINTEMP make it ideal as an aerodynamic and astrodynamic design tool.

B. RECOMMENDATIONS

SKINTEMP currently calculates the insulated skin temperature and heat flow rate at only one surface location. The computer code could be expanded to perform a thermal nodal analysis that could predict skin temperatures along an extended surface. Moreover, temperatures of materials within the air/spacecraft affected by the skin temperature could be calculated. This would be very useful in the design process to initially identify hot spots which, especially in hypersonic flight, could be crucial to the overall design. SKINTEMP was written strictly for the turbulent flow case because this generally produces worst case skin temperatures. The code could easily be modified to model laminar flow if turbulent flow was not the required assumption.

Because the skin temperature problem is quite detailed and the inputs are extensive, complete trajectory and corresponding surface skin temperatures profiles are difficult to find in the literature. Additional test cases could be developed for SKINTEMP for further validation as well as any experimental data that is available.

The important objective to remember in any significant code modification of SKINTEMP is that the program needs to run quickly and allow the user to modify any design parameters. If the program becomes too complex and time consuming, then the usefulness of SKINTEMP is degraded.

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APPENDIX A.   SKINTEMP COMPUTER CODE

```
****************************************************************
*   LT Mary L. Cummings                                        *
*   591                                                        *
*                                                              *
*   This program calculates transient mission aerodynamic heating *
*     parameters (Adiabatic wall temperatures, local heat transfer *
*     coeffcients, and insulated skin temperatures) using various *
*     basic flight parameters as input.                        *
****************************************************************


****************************************************************
*                                                              *
*   Variable declarations                                      *
*                                                              *
*        BODY - determines shape of body, either wing or       *
*               axisymmetric                                   *
*                                                              *
*        SWEEP - angle of wing sweep (degrees)                 *
*                                                              *
*        TEMP - launch vehicle temperature (Fahrenheit)        *
*                                                              *
*        NUMDAT - number of lines of data                      *
*                                                              *
*        TABLE - input data consisting of time (sec), Mach number, *
*                of attack (degrees), and height (feet)        *
*                                                              *
*        X - distance from leading edge to point of interest (feet) *
*                                                              *
*        THIN - thickness of interest point (inches)           *
*                                                              *
*        RAD - nose radius of body  (ft)                       *
*                                                              *
*        MATDENS - material density (lbm/ft^3)                 *
*                                                              *
*        MATEMIS - material emissivity                         *
*                                                              *
*        MATSPHT - material specific heat (BTU/lbm-F)          *
*                                                              *
*        TEMPRAD - radiation temperature (Fahrennheit)         *
*                                                              *
*        ANGLE - angle from the unit surface normal to the     *
*                freestream  (degrees)                         *
*                                                              *
*        PRINTOUT - user defined print time (seconds)          *
*                                                              *
*        g - acceleration/weight constant (lbm-ft/lbf-sec^2)   *
*                                                              *
*        L1 - temperature lapse rate from 0 - 36089 ft (R/ft)  *
*                                                              *
*        L2 - temperature lapse rate from 82021 - 154200 ft (R/ft) *
*                                                              *
*        R - gas constant (ft-lbf/slug-R)                      *
*                                                              *
*        TH - thickness of interest point (feet)               *
*                                                              *
*        Densin - initial density at sea level (slug/ ft^3)    *
*                                                              *
*        Pin - initial pressure at sea level (lbf/ft^2)        *
*                                                              *
*        Tempin - launch vehicle temperature (Rankine)         *
*                                                              *
*        T/atmT - freestream temperature (Rankine)             *
*                                                              *
*        P/atmpr - freestream pressure (lbf/ft^2)              *
```

DENS/atmdens - freestream density (slug/ ft^3)

PressT - pressure at the troposphere ceiling (lbf/ft^2)

DensT - density at the troposphere ceiling (slug/ ft^3)

Ptl - local stagnation pressure (lbf/ft^2)

Pt - freestream stagnation pressure (lbf/ft^2)

Tt - freestream stagnation temperature (Rankine)

Ma - calculated freestream Mach number

M1 - Mach number behind shock wave

Ml - local Mach number

a - freestream sonic velocity (ft/sec)

V - freestream velocity (ft/sec)

q - dynamic pressure (slug/ft-sec^2)

gamma - ratio of specific heat at constant pressure to
        specific heat at constant volume

sigma - Stefan-Boltzmann constant (BTU/hr-ft^2-R^4)

theta - angle of attack added to the normal freestream
        angle (radians)

CpMax - Maximum pressure coefficient

Pl - local pressure (lbf/ft^2)

Ttl - local stagnation temperature (Rankine)

Tl - local temperature (Rankine)

Tn - skin tempertaure (Rankine)

TAW - adiabatic wall temperature (Rankine)

re - recovery factor

Pr - Prandtl number

u - viscosity (slug/sec-ft)

k - thermal conductivity (BTU/sec-ft-F)

C1 - Sutherland's constant (slug/ft-sec-R^.5)

C2 - Sutherland's constant (Rankine)

Cp - specific heat (BTU/lbm-R)

Tstar - reference temperature (Rankine)

denstar - reference density (slug/ft^3)

ustar - reference viscosity (slug/sec-ft)

al - local sonic velocity (ft/sec)

```
*        V1 - local velocity (ft/sec)                           *
*                                                                *
*        Restar - reference Reynolds number                     *
*                                                                *
*        Cpstar - reference specific heat (BTU/lbm-R)           *
*                                                                *
*        kstar - reference thermal conductivity (BTU/sec-ft-F)  *
*                                                                *
*        Prstar - reference Prandtl number                      *
*                                                                *
*        NUstar - reference Nusselt number                      *
*                                                                *
*        h - local heat| transfer coefficient (BTU/sec-ft^2-F)  *
*                                                                *
*        w - specific weight (lbf/ft^3)                         *
*                                                                *
*        TEMPNEX -   skin temperature calculated based on the   *
*                    previous skin temperature (Rankine)        *
*                                                                *
*        Hr - time differential calculation aid                 *
*                                                                *
*        time - time step (sec)                                 *
*                                                                *
*        sumtime - interval time counter (sec)                  *
*                                                                *
*        runtime - total time counter (sec)                     *
*                                                                *
*        printtime - time printing counter (sec)                *
*                                                                *
*        stagpt - stagnation point (ft)                         *
*                                                                *
*                                                                *
*        ANGLER - Angle of attack (radians)                     *
*                                                                *
*        hsl - stagnation enthalpy (BTU/lbm)                    *
*                                                                *
*        hws - wall enthalpy (BTU/lbm)                          *
*                                                                *
*        hw540 - wall enthalpy at 540 R (BTU/lbm)               *
*                                                                *
*        qstag - stagnation point heating rate (BTU/sec)        *
*                                                                *
*        qheat - heat transferred (BTU/sec)                     *
*                                                                *
**********************************************************************

      dimension TABLE(100,4), T(100), P(100), DENS(100)

      integer BODY, NUMDAT

      real SWEEP, TEMP, TABLE, X, THIN, RAD, MATDENS, MATEMIS,
   c  MATSPHT, TEMPRAD, ANGLE, TH, PRINTOUT, g, L1, L2, L3, R,
   c  Densin, Pin, Tempin, T, P, DENS, PressT, DensT,
   c  atmpr, atmdens, atmT, Pt1, Pt, Tt, M1, a, V, q, Ma,
   c  gamma, sigma, theta, pi, printtime,
   c  CpMax, P1, M1, Tt1, T1, Tn, TAW, re, Pr, u, k, C1, C2,
```

```
      c Cp, Tstar, denstar, ustar, al, Vl, Restar, Cpstar,

      c kstar, Prstar, NUstar, h, w, TEMPNEX, HR, time,

      c stagpt, ANGLER, hsl, hws, hw540, qstag, qheat,

      c timedif, sumtime, deltatime, deltam


***********************************************************************
*                                                                     *
*                                                                     *
*  Input                                                              *
*                                                                     *
***********************************************************************

      print *

      print *, 'If the body is axisymmetric, enter 1.'
      print *, 'If the body is a wing, enter 2.'

      read *, BODY

      print *

      if (BODY .EQ. 2) then

         print *, 'What is the wing sweep?'

         read *, SWEEP

         print *

      end if

      print *, 'What is the launch temperature of the vehicle? (F)'

      read *, TEMP

      print *

      print *, 'How many data points will be entered for time, Mach num
     c ber, angle of attack,'
      print *, 'and altitude?'

      read *, NUMDAT

      print *

      print *, 'Enter the time (s), Mach number, angle of attack (degr
     c ees), and altitude (ft)    in a row/column format.'
      print *, 'Hit return after every entry.'
      print *
      print *, '***WARNING*** Do not use any data lines with M - 0'

      Do 20 ROW=1, NUMDAT

        Do 10 COL=1,4

           read *, TABLE(ROW,COL)

10         continue

20      continue
```

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```
      print *

      print *, 'What is the distance from the tip of the vehicle to the
     c point of interest? (ft)'

      read *, X

      print *

      print *, 'What is the thickness of the surface at the point of in
     c terest? (in)'

      read *, THIN

      print *

      print *, 'What is the nose radius? (ft)'

      read *, RAD

      print *

      print *, 'What is the density of the material? (lbm/ft^3)'

      read *, MATDENS

      print *

      print *, 'What is the emissivity of the material?'

      read *, MATEMIS

      print *

      print *, 'What is the specific he__ of the material used? (BTU/lb
     cm-F)'

      read *, MATSPHT

      print *

      print *, 'For the majority of the flight path, if the surface rad
     ciates towards the earth,    enter 60.'
      print *, 'If it radiates to space, enter 0.'

      read *, TEMPRAD

      print *

      print *, 'What is the angle from the unit surface normal to the
     cfreestream? (degrees)'

      read *, ANGLE

      print *

      print *, 'What time increment would you like the skin temperature
     cs printed? (seconds)'

      read *, PRINTOUT

      print *
******************************************************************************
```

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```
gamma = 1.4
sigma = .1714E-8/3600.0
pi = 3.1415927
TH = THIN/12.0
sumtime = 0.
deltatime = 0.
printtime = printout

if (TEMPRAD .EQ. 60) then
        TEMPRAD = TEMPRAD + 460.
end if


do 100 n = 1, NUMDAT

    if (n .EQ. 1) then
        Tn = Tempin
        Ma = TABLE(n,2)
        atmpr = P(n)
        atmdens = Dens(n)
        atmT = T(n)

        if (BODY .EQ. 2) then
          Ma = Ma * cos(sweep * pi/180.)
        end if

        timedif = (TABLE(n+1,1) - TABLE(n,1))
        GOTO 60
      end if

    deltam = (TABLE(n+1,2) - TABLE(n,2))
    timedif = (TABLE(n+1,1) - TABLE(n,1))

50      if (sumtime .GT. 0.) then
```

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```
*  Atmospheric data calculations                                          *
*                                                                         *
*************************************************************************

       g - 32.174

       L1 - -.0035665

       L2 - .001645

       L3 - -.002469

       R - 1716.

       Densin - .002378

       Pin - 2116.0

       Tempin - TEMP + 460.0


       do 30 HGT - 1, NUMDAT

          if (TABLE(HGT,4) .LE. 36089.0) then
*             Troposphere

              T(HGT) - Tempin + L1 * TABLE(HGT,4)

              P(HGT) - Pin * (T(HGT)/Tempin)**(-g/(L1 * R ))

              DENS(HGT) - Densin * ((T(HGT)/Tempin)**-(g/(L1 * R)
     c                    + 1))

               goto 30
          end if
*             Stratosphere

          if (TABLE(HGT,4) .GE. 82021) then


              if (TABLE(HGT,4) .GE. 173885) then

                T(HGT) - 509 + L3 *(TABLE(HGT,4) - 173885)

                P(HGT) - 1.5 * (T(HGT)/509)**(-g/(L3 * R ))

                DENS(HGT) - .0000014 * ((T(HGT)/509)**
     c                      -((g/(L3 * R))+ 1.0))

               goto 30
              end if

              if (TABLE(HGT,4) .GE. 154200) then

                T(HGT) - 509

                PressT - 2.6419                                  /
```

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```fortran
               DensT = .00000303

               P(HGT) = PressT * EXP (-((g / (R * T(HGT))) *
     c              (TABLE(HGT,4) - 154200.)))

               DENS(HGT) = DensT * P(HGT) / PressT

               goto 30

            end if

          T(HGT) = 389.9 + L2 * (TABLE(HGT,4) - 82021.)

          P(HGT) = 55.8 * (T(HGT)/389.97)**(-g/(L2 * R ))

          DENS(HGT) = .0000789 * ((T(HGT)/389.97)**
     c                 -((g/(L2 * R))+ 1.0))

          goto 30

        end if

          T(HGT) = -67.5 + 460.0

             PressT = 476

             DensT = .000710

          P(HGT) = PressT * EXP (-((g / (R * T(HGT))) * (
     c              TABLE(HGT,4) - 36089.)))

          DENS(HGT) = DensT * P(HGT) / PressT


30        continue

***********************************************************************
*                                                                     *
*  Header                                                             *
*                                                                     *
***********************************************************************

      print *
      print *
      print *
      print *

      print 40, 'Time', 'Adiabatic Wall', 'Heat Transfer',
     c'Skin Temp', 'Heat Transfer Rate '

      print 45, '(sec)', ' Temperature (R)',  'Coefficient', ' (R)',
     c   ' (BTU/sec-one sq ft)'

      print *

40    Format(2X, A4, 2X, A16, 1X, A16, 3X, A9, 5X, A21)

45    Format(2X, A5, 2X, A16, 4X, A11, 6X, A4, 8X, A21)


***********************************************************************
*                                                                     *
*  Subsonic vs supersonic calculations                               *
*                                                                     *
```

```fortran
              Ma = sumtime * deltam/(timedif) + TABLE(n,2)

              atmpr = P(n) + sumtime * (P(n+1) - P(n))/timedif

              atmdens =  Dens(n) + sumtime * (Dens(n+1) - Dens(n))
     c                   /timedif

              atmT =   T(n) + sumtime*(T(n+1)-T(n))/timedif

                if (BODY .EQ. 2) then

                    Ma = Ma * cos(sweep * pi/180.)

                end if

            end if

             if (sumtime .EQ. 0 ) then

             Ma = TABLE(n,2)

             atmpr = P(n)

             atmdens =  Dens(n)

             atmT =  T(n)

             if (BODY .EQ. 2) then

                    Ma = Ma * cos(sweep * pi/180.)

                 end if

            end if

60          if (Ma .LE. 1.0) then

                Ptl = atmpr * (1.0 + ((gamma-1.0)/2.0) * Ma**2)**
     c             (gamma/(gamma-1.0))

            else

                Pt = atmpr * (1.0 + ((gamma-1.0)/2.0) * Ma**2)**
     c             (gamma/(gamma-1.0))

                Tt = atmT * (1.0 + ((gamma-1.0)/2.0) * Ma**2)

                Ptl = Pt * (((gamma+1.0)/2 * Ma**2)/(1 + (gamma
     c             -1.0)/2 * Ma**2))**(gamma/(gamma-1.0)) *
     c             (2.0*gamma/(gamma+1.0) * Ma**2 -(gamma-1.0)/
     c             (gamma+1.0))**(1/(1-gamma))

            end if

************************************************************************
*                                                                     *
*  Adiabatic wall temperature calculations                            *
*                                                                     *
************************************************************************
```

46

```
             a = (gamma * R * atmT)**.5

             V = a * Ma

             q = .5 * atmdens * V**2

             theta = (ANGLE  + TABLE(n,3)) * pi/180.

             CpMax = (Pt1 -  atmpr)/q

             Pl = q*CpMax * (cos(theta))**2 + atmpr

             Ml = (((Pt1/Pl)**((gamma-1.0)/gamma)-1.0) * (2.0/
    c                (gamma-1.0)))**.5

             Ttl = atmT * (1.0 + (gamma-1.0)/2.0 * Ma**2)

             Tl = Ttl/(1.0 + (gamma-1.0)/2.0 * Ml**2)

             k = (.0141 * (717.0/(Tl + 225.)) * (Tl/492.0)
    c              **1.5)/3600.0

             Cp = .219 + .342E-4 * Tl - .293E-8 * Tl**2

             C1 = 2.27E-8

             C2 = 198.7

             u = C1 * Tl**1.5/(Tl + C2)

             Pr = Cp * u * g /k

             re = Pr**(1.0/3.0)

             TAW = Tl * (1.0+re * (gamma-1.0)/2.0 * Ml**2)
```

```
*********************************************************************
*                                                                   *
*   Heat transfer coefficient calculations                          *
*                                                                   *
*********************************************************************
```

```
             Tstar = Tl + .5 * (Tn-Tl) + .22 * (TAW-Tl)

             denstar = Pl/(R * Tstar)

             ustar = (C1 * Tstar**1.5)/(Tstar + C2)

             al = (gamma * R * Tl)**.5

             Vl = al * Ml

             Restar = denstar * Vl * X/ustar

             Cpstar = .219 + .342E-4 * Tstar - .293E-8 * Tstar
    c                 **2


             kstar = (.0141 * (717.0/(Tstar + 225.)) * (Tstar/
    c                 492.0)**1.5)/3600.0

             Prstar = Cpstar * g * ustar/kstar
```

```fortran
            if (Restar .LE. 1.E7) then

                    NUstar = .0292 * (Restar**.8) * (Prstar
    c                       **(1.0/3.0))

                else

                    NUstar = .185 * (Restar) * (Prstar)**
    c                       (1.0/3.0)/((log10(Restar))**
    c                       2.584)

            end if


            h = NUstar * kstar/X


*****************************************************************
*                                                               *
*   Skin temperature calculations                               *
*                                                               *
*****************************************************************

            w = MATDENS / g

            Hr = MATEMIS * sigma * (Tn**3 + Tn**2 * TEMP
    c            RAD + TEMPRAD**2 * Tn + TEMPRAD**3)

            time =   .25 * MATSPHT * w * g * th /(hr + h)

            TEMPNEX = time*(((h * 1 *(TAW-Tn))
    c            - sigma * MATEMIS * (Tn**4-Tr**4))/
    c            (MATSPHT * w * g * TH * 1)) + Tn


*****************************************************************
*                                                               *
*   Stagnation point heat transfer calculation                  *
*                                                               *
*****************************************************************

        ANGLER = ANGLE * pi/180.

        hsl = Cp * Ttl

        hws = Cp * Tn

        hw540 = Cp * 540.

        stagpt = cos(70 * (pi/180.))

        if (ANGLER .LE. stagpt) then

            qstag = 17600.0/SQRT(RAD) * SQRT(atmdens/Densin) * (V/
    c            26000.0)**3.15 * ((hsl-hws)/(hsl-hw540))

          if (BODY .EQ. 1) then

            qheat = qstag * (cos(ANGLER)**(3.0/2.0))

            else

            qheat = qstag * (cos(ANGLER)**(3.0/2.0))/SQRT(2.0)
```

```
                         end if

                else

*                 ********************************************
*                 *                                          *
*                 * Heat transfer calculation                *
*                 *                                          *
*                 ********************************************

                  qheat - h * l * (TAW-Tn) - sigma *
     c                    MATEMIS * (Tn**4-TEMPRAD**4)


                end if

        Tn - Tempnex

        sumtime - sumtime + time

        runtime - runtime + time

        Tf - Tempnex

          if (sumtime .GE. timedif) then

            deltatime - sumtime - timedif

            if (runtime .GE. printtime) then

                Print 80, printtime, TAW, h, Tf, qheat

                WRITE(3,90) printtime, TEMPNEX

                printtime - (printtime + printout)
            end if

            sumtime - 0

            goto 100

          else

            if (n .GE. numdat) then

                goto 100

            end if

              GOTO 50

          end if


************************************************************************
*                                                                    *
*    Output                                                          *
*                                                                    *
************************************************************************
```

```
80      Format( 0X, F7.2, 5X, F9.2, 10X, F8.6, 5X, F9.2, 12X, F8.3)

90      Format(1X, F7.2, 10X, F9.3)


100     continue
        print *
        print *
        print *


        end
```

APPENDIX B. EXAMPLE SKINTEMP INPUT AND OUTPUT

What is the launch temperature of the vehicle? (F)

How many data points will be entered for time, Mach number, angle of attack, and altitude?

Enter the time (s), Mach number, angle of attack (degrees), and altitude (ft) in a row/column format.
Hit return after every entry.

WARNING Do not use any data lines with M = 0

What is the distance from the tip of the vehicle to the point of interest? (ft)

What is the thickness of the surface at the point of interest? (in)

What is the nose radius? (ft)

What is the density of the material? (lbm/ft^3)

What is the emissivity of the material?

What is the specific heat of the material used? (BTU/lbm-F)

For the majority of the flight path, if the surface radiates towards the earth, enter 60.
If it radiates to space, enter 0.

What is the angle from the unit surface normal to the freestream? (degrees)

What time increment would you like the skin temperatures printed? (seconds)

SKINTEMP data entry prompts

51

```
1
59
32
1
.36
0
2<0
2
.718
0
500
3
1.08
0
750
4
1.445
0
1000
5
1.816
0
1500
6
1.735
0
2000
7
1.65
0
3000
8
1.570
0
5000
9
1.48
0
9500
10
1.397
0
10000
11
2.107
0
13000
12
2.83
0
15000
13
3.575
0
18000
14
4.348
0
22000
15
5.157
0
25000
16
5.095
0
27000
17
5.03
0
```

Date entered using the file entry method (Truitt test case)

```
34000
18
4.959
0
37000
19
4.804
0
40000
20
4.649
0
46000
21
5.80
0
50000
22
6.951
0
52000
23
8.103
0
62000
24
9.254
0
66000
25
10.373
0
69000
26
11.521
0
85000
27
12.67
0
89500
28
13.817
0
95000
29
14.43
0
117000
30
15
0
125000
31
15
0
125000
32
15
0
125000
20
.005004
.05
530
.9
.121
0
90
1
1
```

Data entered using the file entry method (Truitt test case, continued)

Time (sec)	Adiabatic Wall Temperature (R)	Heat Transfer Coefficient	Skin Temp (R)	Heat Transfer Rate (BTU/sec-one sq ft)
1.00	529.30	0.008575	522.02	0.041
2.00	609.95	0.019815	560.91	1.244
3.00	698.44	0.024123	633.11	2.018
4.00	793.95	0.025823	717.28	2.503
5.00	794.17	0.024537	772.03	0.526
6.00	760.86	0.023045	767.06	-0.392
7.00	725.14	0.021186	742.17	-0.660
8.00	674.31	0.017698	704.24	-0.854
9.00	656.61	0.017273	677.72	-0.611
10.00	792.45	0.019156	707.28	2.048
11.00	1042.91	0.019434	850.20	4.754
12.00	1397.34	0.017993	1091.53	6.712
13.00	1859.94	0.015438	1408.19	7.561
14.00	2451.81	0.013316	1761.73	7.877
15.00	2457.28	0.011619	1917.23	0.815
16.00	2257.59	0.008788	1845.07	-2.340
17.00	2202.84	0.008247	1781.19	-1.444
18.00	2096.52	0.007287	1711.37	-1.503
19.00	1979.69	0.005898	1626.52	-1.607
20.00	2740.36	0.005182	1704.54	3.274
21.00	3870.34	0.004645	1967.57	5.554
22.00	5010.18	0.003351	2131.51	2.475
23.00	6573.34	0.002756	2259.56	2.906
24.00	8142.86	0.002458	2374.87	2.701
25.00	9968.20	0.001562	2319.48	-2.354
26.00	12715.81	0.001156	2297.95	0.757
27.00	12728.18	0.001152	2300.75	0.071
28.00	15484.49	0.000928	2310.05	0.229
29.00	18435.02	0.000420	2071.97	-5.430
30.00	20525.59	0.000321	1952.78	-1.970
31.00	20525.59	0.000323	1936.63	-0.227
32.00	20525.59	0.000324	1935.69	-0.013

SKINTEMP output (Truitt test case)

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